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Generalized parallelogram law for operators and its application

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Abstract. The classical Bohr inequality says that $|a + b|^2 \leq p|a|^2 + q|b|^2$ for all scalars a, b and $p, q > 0$ with $1/p + 1/q = 1$. In this note, we improve the accuracy of the estimate given by the original Bohr inequality. Actually, we present:

If A and B are operators on a Hilbert space and $t \neq 0$, then

$$|A + B|^2 + \frac{1}{t}|tA - B|^2 = (1 + t)|A|^2 + (1 + \frac{1}{t})|B|^2.$$

We discuss applications and further generalizations of it.

§1 Introduction

Let H be a complex separable Hilbert space and $\mathcal{B}(H)$ the algebra of all bounded operators on H . Denote by $|A|$ the absolute value operator of $A \in \mathcal{B}(H)$: $|A| = (A^*A)^{1/2}$, where A^* is the adjoint operator of A .

We say that A is a positive operator, if $(Ax, x) \geq 0$ for all $x \in H$, denoted by $A \geq 0$, and $A \geq B$ if A and B are self-adjoint and $A - B \geq 0$.

The classical Bohr inequality for scalar asserts that for any $a, b \in \mathbb{C}$ and all positive conjugate exponents $p, q \in \mathbb{R}$,

$$|a + b|^2 \leq p|a|^2 + q|b|^2 \quad (0)$$

with equality if and only if $(1 - p)a = b$ (See [1]).

In 2003, O. Hirzallah[4] proposed an operator version of Bohr inequality as follows:

If $A, B \in \mathcal{B}(H)$ and p, q are both positive real conjugate exponents with $q \geq p$, then

$$|A - B|^2 + |(p - 1)A + B|^2 \leq p|A|^2 + q|B|^2. \quad (1)$$

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It is well known that the absolute value operator plays an important role in the polar decomposition $A = U|A|$. Recently, various generalizations of Bohr inequalities have been obtained in [2] and [6].

In this paper, we improve the accuracy of the estimate given by the original Bohr inequality. As a matter of fact, the parallelogram law for absolute value of operators:

$$|A + B|^2 + |A - B|^2 = 2|A|^2 + 2|B|^2 \quad (2)$$

is our viewpoint. An operator version of the Bohr inequality (0) is obtained by a generalization of (2) as follows:

$$|A + B|^2 + |\sqrt{p-1}A - \sqrt{q-1}B|^2 = p|A|^2 + q|B|^2 \quad (3)$$

for operators A, B , and $p, q \geq 1$ with $\frac{1}{p} + \frac{1}{q} = 1$, because of $(p-1)(q-1) = 1$.

Furthermore, we extend the Bohr inequality to a three variable case:

If $\frac{1}{p} + \frac{1}{q} + \frac{1}{w} = 1$ for $p, q, w > 0$, then for operators A, B, C , we have

$$|A + B + C|^2 \leq p|A|^2 + q|B|^2 + w|C|^2.$$

§2 Bohr equality for 2 operators

The operator parallelogram law (2) has also the following generalization, which is different from (3) a bit:

Theorem 2.1 If $A, B \in \mathbb{B}(H)$, then $|A + B|^2 + \frac{1}{t}|tA - B|^2 = (1+t)|A|^2 + (1+\frac{1}{t})|B|^2$, for $t \neq 0$.

Proof. It follows that

$$\begin{aligned} & |A + B|^2 + \frac{1}{t}|tA - B|^2 \\ &= |A|^2 + |B|^2 + A^*B + B^*A + t|A|^2 + \frac{1}{t}|B|^2 - A^*B - B^*A \\ &= (1+t)|A|^2 + (1+\frac{1}{t})|B|^2. \end{aligned}$$

It is immediately obtained from the condition of t .

Corollary 2.2 (i) If $0 < t \leq 1$, then $|A + B|^2 + |tA - B|^2 \leq (1+t)|A|^2 + (1+\frac{1}{t})|B|^2$;

(ii) If $t \geq 1$ or $t < 0$, then $|A + B|^2 + |tA - B|^2 \geq (1+t)|A|^2 + (1+\frac{1}{t})|B|^2$.

As an easy consequence, we have Bohr type inequalities obtained in [2] and [4].

Corollary 2.3 [4, Theorem 1] If $A, B \in \mathbb{B}(H)$, $\frac{1}{p} + \frac{1}{q} = 1$, $1 \leq p \leq 2$, then

$$(i) \quad |A - B|^2 + |(p-1)A + B|^2 \leq p|A|^2 + q|B|^2.$$

$$(ii) \quad |A - B|^2 + |A + (q-1)B|^2 \geq p|A|^2 + q|B|^2.$$

Corollary 2.4 [2, Theorem 2] If $A, B \in \mathbb{B}(H)$, $\frac{1}{p} + \frac{1}{q} = 1$, $p < 1$, then

$$(iii) \quad |A - B|^2 + |(p-1)A + B|^2 \geq p|A|^2 + q|B|^2.$$

Corollary 2.5 [2, Theorem 3] If $A, B \in \mathbb{B}(H)$, $|\alpha| \geq |\beta|$, then

$$|A - B|^2 + \frac{1}{|\alpha|^2}|\beta|A + |\alpha|B|^2 \leq (1 + \frac{|\beta|}{|\alpha|})|A|^2 + (1 + \frac{|\alpha|}{|\beta|})|B|^2$$

with equality if and only if $|\alpha| = |\beta|$ or $|\beta|A + |\alpha|B = 0$;

§3 Bohr-type inequalities for 3 operators

Observe that

$$|A + B + C|^2 = \begin{pmatrix} I & I & I \end{pmatrix} \begin{pmatrix} |A|^2 & A^*B & A^*C \\ B^*A & |B|^2 & B^*C \\ C^*A & C^*B & |C|^2 \end{pmatrix} \begin{pmatrix} I \\ I \\ I \end{pmatrix} \geq 0.$$

Then, due to the idea of [6], we may convert a problem of absolute operators to a problem of 3×3 block operator matrices, while the later approach maybe easier to handle.

For the sake of convenience, we cite the following well-known fact:

Lemma 3.1 If $x, y, z \geq 0$, and $a, b, c \in \mathbb{R}$ with

$$\begin{cases} xy \geq a^2, yz \geq c^2, xz \geq b^2; \\ xyz + 2abc \geq xc^2 + yb^2 + za^2. \end{cases}$$

Then

$$\begin{pmatrix} x & a & b \\ a & y & c \\ b & c & z \end{pmatrix} \geq 0.$$

Lemma 3.2 Let $A_i \in \mathbb{B}(H)$, $\alpha_i, \beta_i \in \mathbb{R}$ with $i = 1, 2, 3$. Then positive operator-valued function

$$F(\alpha_1, \alpha_2, \alpha_3) = |\alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3|^2$$

is order preserving if the order \prec among \mathbb{R} is defined by

$$(\alpha_1, \alpha_2, \alpha_3) \prec (\beta_1, \beta_2, \beta_3) \Leftrightarrow |\alpha_i| \leq |\beta_i| \text{ for all } i \text{ and } \alpha_i \beta_j = \alpha_j \beta_i \text{ for } i \neq j.$$

Proof. Since $|A_1 + A_2 + A_3|^2 = \begin{pmatrix} I & I & I \end{pmatrix} \begin{pmatrix} A_1^* \\ A_2^* \\ A_3^* \end{pmatrix} \begin{pmatrix} A_1 & A_2 & A_3 \end{pmatrix} \begin{pmatrix} I \\ I \\ I \end{pmatrix},$

it suffice to show that $(\alpha_1, \alpha_2, \alpha_3) \prec (\beta_1, \beta_2, \beta_3)$ implies that

$$\begin{pmatrix} \alpha_1 A_1^* \\ \alpha_2 A_2^* \\ \alpha_3 A_3^* \end{pmatrix} \begin{pmatrix} \alpha_1 A_1 & \alpha_2 A_2 & \alpha_3 A_3 \end{pmatrix} \leq \begin{pmatrix} \beta_1 A_1^* \\ \beta_2 A_2^* \\ \beta_3 A_3^* \end{pmatrix} \begin{pmatrix} \beta_1 A_1 & \beta_2 A_2 & \beta_3 A_3 \end{pmatrix},$$

that is,

$$\begin{pmatrix} \alpha_1^2 |A_1|^2 & \alpha_1 \alpha_2 A_1^* A_2 & \alpha_1 \alpha_3 A_1^* A_3 \\ \alpha_1 \alpha_2 A_2^* A_1 & \alpha_2^2 |A_2|^2 & \alpha_2 \alpha_3 A_2^* A_3 \\ \alpha_1 \alpha_3 A_3^* A_1 & \alpha_2 \alpha_3 A_3^* A_2 & \alpha_3^2 |A_3|^2 \end{pmatrix} \leq \begin{pmatrix} \beta_1^2 |A_1|^2 & \beta_1 \beta_2 A_1^* A_2 & \beta_1 \beta_3 A_1^* A_3 \\ \beta_1 \beta_2 A_2^* A_1 & \beta_2^2 |A_2|^2 & \beta_2 \beta_3 A_2^* A_3 \\ \beta_1 \beta_3 A_3^* A_1 & \beta_2 \beta_3 A_3^* A_2 & \beta_3^2 |A_3|^2 \end{pmatrix}.$$

By the definition and Lemma 3.1, we have

$$\begin{pmatrix} \beta_1^2 - \alpha_1^2 & \beta_1\beta_2 - \alpha_1\alpha_2 & \beta_1\beta_3 - \alpha_1\alpha_3 \\ \beta_1\beta_2 - \alpha_1\alpha_2 & \beta_2^2 - \alpha_2^2 & \beta_2\beta_3 - \alpha_2\alpha_3 \\ \beta_1\beta_3 - \alpha_1\alpha_3 & \beta_2\beta_3 - \alpha_2\alpha_3 & \beta_3^2 - \alpha_3^2 \end{pmatrix} \geq 0,$$

which implies the conclusion.

Theorem 3.3 Let $A, B, C \in \mathbb{B}(H)$, $\alpha_i \in \mathbb{R}$, $p, q, w > 0$ with $i = 1, 2, 3$. If

$$\begin{cases} p \geq \alpha^2; \\ q \geq \beta^2; \\ w \geq \gamma^2. \end{cases} \begin{cases} (p - \alpha^2)(q - \beta^2) \geq (\alpha\beta)^2; \\ (q - \beta^2)(w - \gamma^2) \geq (\beta\gamma)^2; \\ (w - \gamma^2)(p - \alpha^2) \geq (\gamma\alpha)^2; \\ pqw \geq \alpha^2qw + \beta^2pw + \gamma^2pq. \end{cases}$$

Then

$$|\alpha A + \beta B + \gamma C|^2 \leq p|A|^2 + q|B|^2 + w|C|^2.$$

Proof. As in above, we have to show that

$$\begin{pmatrix} \alpha^2|A|^2 & \alpha\beta A^*B & \alpha\gamma A^*C \\ \alpha\beta B^*A & \beta^2|B|^2 & \beta\gamma B^*C \\ \alpha\gamma C^*A & \beta\gamma C^*B & \gamma^2|C|^2 \end{pmatrix} \leq \begin{pmatrix} p|A|^2 & 0 & 0 \\ 0 & q|B|^2 & 0 \\ 0 & 0 & w|C|^2 \end{pmatrix}.$$

Therefore, what we should do is just to prove that

$$\begin{pmatrix} p - \alpha^2 & \alpha\beta & \alpha\gamma \\ \alpha\beta & q - \beta^2 & \beta\gamma \\ \alpha\gamma & \beta\gamma & w - \gamma^2 \end{pmatrix} \geq 0,$$

which is obtained by the assumption and Lemma 3.1.

The following corollary is symmetric to Theorem 3.3.

Corollary 3.4 Let $A, B, C \in \mathbb{B}(H)$, $\alpha_i \in \mathbb{R}$, $p, q, w > 0$ with $i = 1, 2, 3$. If

$$\begin{cases} p \leq \alpha^2; \\ q \leq \beta^2; \\ w \leq \gamma^2. \end{cases} \begin{cases} (p - \alpha^2)(q - \beta^2) \geq (\alpha\beta)^2; \\ (q - \beta^2)(w - \gamma^2) \geq (\beta\gamma)^2; \\ (w - \gamma^2)(p - \alpha^2) \geq (\gamma\alpha)^2; \\ pqw \geq \alpha^2qw + \beta^2pw + \gamma^2pq. \end{cases}$$

Then

$$|\alpha A + \beta B + \gamma C|^2 \geq p|A|^2 + q|B|^2 + w|C|^2.$$

Now we have Bohr inequality for 3 operators.

Corollary 3.5 If $p, q, w > 0$, $\frac{1}{p} + \frac{1}{q} + \frac{1}{w} = 1$, then $|A + B + C|^2 \leq p|A|^2 + q|B|^2 + w|C|^2$.

Proof. Given $p, q, w > 0$, $\frac{1}{p} + \frac{1}{q} + \frac{1}{w} = 1$, the following is

$$\begin{cases} p \geq 1; \\ q \geq 1; \\ w \geq 1. \end{cases} \begin{cases} (p - 1)(q - 1) \geq 1; \\ (q - 1)(w - 1) \geq 1; \\ (w - 1)(p - 1) \geq 1; \\ pqw = qw + pw + pq. \end{cases}$$

Therefore, Theorem 3.3 implies that

$$|A + B + C|^2 \leq p|A|^2 + q|B|^2 + w|C|^2.$$

§4 Bohr equality for multiple operators

For this, we begin with the reformulation of (3). As a matter of fact, it is just the first step in this section:

Lemma 4.1 Let $A_1, A_2 \in \mathbb{B}(H)$, $\frac{1}{r_1} + \frac{1}{r_2} = 1$ with $r_1, r_2 \geq 1$.

$$r_1|A_1|^2 + r_2|A_2|^2 - |A_1 + A_2|^2 = \left| \sqrt{\frac{r_1}{r_2}}A_1 - \sqrt{\frac{r_2}{r_1}}A_2 \right|^2.$$

Theorem 4.2 Suppose that $A_i \in \mathbb{B}(H)$, and $r_i \geq 1$ with $\sum_{i=1}^n \frac{1}{r_i} = 1$ for $i = 1, 2, \dots, n, n \in \mathbb{N}$. Then

$$\sum_{i=1}^n r_i|A_i|^2 - \left| \sum_{i=1}^n A_i \right|^2 = \sum_{1 \leq i < j \leq n} \left| \sqrt{\frac{r_i}{r_j}}A_i - \sqrt{\frac{r_j}{r_i}}A_j \right|^2. \quad (4)$$

Proof. We show it by the induction on n . Note that it is true for $n = 2$ by Lemma 4.1. Now suppose that it is true for $n = k$, then we take $A_1, \dots, A_{k+1} \in \mathbb{B}(H)$ and $r_1, \dots, r_{k+1} > 1$ satisfying $\sum_{i=1}^{k+1} \frac{1}{r_i} = 1$. If we put $r'_i = r_i(1 - \frac{1}{r_{k+1}})$ for $i = 1, \dots, k$ for convenience, then $r'_i > 1$ and $\sum_{i=1}^k \frac{1}{r'_i} = 1$. Hence we have

$$\begin{aligned} & \sum_{i=1}^{k+1} r_i|A_i|^2 - \left| \sum_{i=1}^{k+1} A_i \right|^2 = \sum_{i=1}^k r_i|A_i|^2 + r_{k+1}|A_{k+1}|^2 - \left| \sum_{i=1}^k A_i + A_{k+1} \right|^2 \\ &= \left(1 - \frac{1}{r_{k+1}}\right) \sum_{i=1}^k r_i|A_i|^2 - \left| \sum_{i=1}^k A_i \right|^2 \\ & \quad + (r_{k+1} - 1)|A_{k+1}|^2 + \frac{1}{r_{k+1}} \sum_{i=1}^k r_i|A_i|^2 - \left(\sum_{i=1}^k A_i \right)^* A_{k+1} - A_{k+1}^* \sum_{i=1}^k A_i \\ &= \left(\sum_{i=1}^k r'_i|A_i|^2 - \left| \sum_{i=1}^k A_i \right|^2 \right) + \sum_{i=1}^k \frac{r_i}{r_{k+1}}|A_i|^2 - \left(\sum_{i=1}^k A_i \right)^* A_{k+1} - A_{k+1}^* \sum_{i=1}^k A_i + (r_{k+1} - 1)|A_{k+1}|^2 \\ &= \sum_{1 \leq i < j \leq k} \left| \sqrt{\frac{r_i}{r_j}}A_i - \sqrt{\frac{r_j}{r_i}}A_j \right|^2 + \sum_{i=1}^k \frac{r_i}{r_{k+1}}|A_i|^2 - \left(\sum_{i=1}^k A_i \right)^* A_{k+1} - A_{k+1}^* \sum_{i=1}^k A_i + \sum_{i=1}^k \frac{r_{k+1}}{r_i}|A_{k+1}|^2 \\ &= \sum_{1 \leq i < j \leq k+1} \left| \sqrt{\frac{r_i}{r_j}}A_i - \sqrt{\frac{r_j}{r_i}}A_j \right|^2. \end{aligned}$$

Therefore, the equality (4) holds for all $n \in \mathbb{N}$.

Corollary 4.3 [6, Theorem 7] Suppose that $A_i \in \mathbb{B}(H)$, and $r_i \geq 1$ with $\sum_{i=1}^n \frac{1}{r_i} = 1$ for $i = 1, 2, \dots, n$. Then

$$\left| \sum_{i=1}^n A_i \right|^2 \leq \sum_{i=1}^n r_i|A_i|^2.$$

Equivalently, we can say that $K(z) = |z|^2$ satisfies (operator) Jensen inequality, in the sense that

$$K\left(\sum_{i=1}^n t_i A_i\right) \leq \sum_{i=1}^n t_i K(A_i)$$

for $t_1, \dots, t_n \geq 0$ with $\sum_{i=1}^n t_i = 1$.

Corollary 4.4 Let $A_i \in \mathbb{B}(H)$, $\sum_{i=1}^n \frac{1}{r_i} = 1$, and $r_i \neq 0$ with $\sum_{i=1}^n \frac{1}{r_i} = 1$ for $i = 1, 2, \dots, n$, $n \in \mathbb{N}$.

Then

$$\sum_{i=1}^n r_i |A_i|^2 - \left| \sum_{i=1}^n A_i \right|^2 = \sum_{1 \leq i < j \leq n} \frac{r_j}{r_i} \left| \frac{r_i}{r_j} A_i - A_j \right|^2.$$

§5 Further generalization of Bohr inequality

Theorem 5.1 Let $A, B, C \in \mathbb{B}(H)$, $\alpha_i \in \mathbb{R}$, $\gamma_i > 0$ with $i = 1, 2, 3$. If

$$\begin{cases} \gamma_1 \geq 1 + \alpha_1^2; \\ \gamma_2 \geq 1 + \alpha_2^2; \\ \gamma_3 \geq 1 + \alpha_3^2. \end{cases} \begin{cases} [\gamma_1 - (1 + \alpha_1^2)][\gamma_2 - (1 + \alpha_2^2)] \geq (1 + \alpha_1 \alpha_2)^2; \\ [\gamma_2 - (1 + \alpha_2^2)][\gamma_3 - (1 + \alpha_3^2)] \geq (1 + \alpha_2 \alpha_3)^2; \\ [\gamma_1 - (1 + \alpha_1^2)][\gamma_3 - (1 + \alpha_3^2)] \geq (1 + \alpha_1 \alpha_3)^2. \end{cases}$$

with $[\gamma_1 - (1 + \alpha_1^2)][\gamma_2 - (1 + \alpha_2^2)][\gamma_3 - (1 + \alpha_3^2)] - 2(1 + \alpha_1 \alpha_2)(1 + \alpha_1 \alpha_3)(1 + \alpha_2 \alpha_3) \geq -[\gamma_3 - (1 + \alpha_3^2)](1 + \alpha_1 \alpha_2)^2 - [\gamma_2 - (1 + \alpha_2^2)](1 + \alpha_1 \alpha_3)^2 - [\gamma_1 - (1 + \alpha_1^2)](1 + \alpha_2 \alpha_3)^2$.

Then

$$|A_1 + A_2 + A_3|^2 + |\alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3|^2 \leq \gamma_1 |A_1|^2 + \gamma_2 |A_2|^2 + \gamma_3 |A_3|^2. \quad (5)$$

Proof. Notice that both sides of the inequality (5) correspond to

$$\begin{pmatrix} (1 + \alpha_1^2)|A_1|^2 & (1 + \alpha_1 \alpha_2)A_1^* A_2 & (1 + \alpha_1 \alpha_3)A_1^* A_3 \\ (1 + \alpha_1 \alpha_2)A_2^* A_1 & (1 + \alpha_2^2)|A_2|^2 & (1 + \alpha_2 \alpha_3)A_2^* A_3 \\ (1 + \alpha_1 \alpha_3)A_3^* A_1 & (1 + \alpha_2 \alpha_3)A_3^* A_2 & (1 + \alpha_3^2)|A_3|^2 \end{pmatrix}$$

and

$$\begin{pmatrix} \gamma_1 |A_1|^2 & 0 & 0 \\ 0 & \gamma_2 |A_2|^2 & 0 \\ 0 & 0 & \gamma_3 |A_3|^2 \end{pmatrix}$$

respectively. Hence, it is suffice to show that

$$\begin{pmatrix} \gamma_1 - (1 + \alpha_1^2) & -1 - \alpha_1 \alpha_2 & -1 - \alpha_1 \alpha_3 \\ -1 - \alpha_1 \alpha_2 & \gamma_2 - (1 + \alpha_2^2) & -1 - \alpha_2 \alpha_3 \\ -1 - \alpha_1 \alpha_3 & -1 - \alpha_2 \alpha_3 & \gamma_3 - (1 + \alpha_3^2) \end{pmatrix} \geq 0,$$

which is implied by the assumption and Lemma 3.1.

Corollary 5.2 Let $A, B, C \in \mathbb{B}(H)$, $\alpha_1, \alpha_2, \beta_i \in \mathbb{R}$, $\gamma_i > 0$ with $i = 1, 2, 3$. If

$$\begin{cases} \gamma_1 \geq 1 + \alpha_1^2; \\ \gamma_2 \geq 1 + \alpha_2^2; \\ \gamma_3 \geq 1. \end{cases} \begin{cases} [\gamma_2 - (\alpha_2^2 + 1)](\gamma_3 - 1) \geq 1; \\ [\gamma_1 - (\alpha_1^2 + 1)](\gamma_3 - 1) \geq 1; \\ [\gamma_1 - (\alpha_1^2 + 1)][\gamma_2 - (\alpha_2^2 + 1)] \geq (1 + \alpha_1 \alpha_2)^2; \\ 1 + \alpha_1 \alpha_2 \leq 0. \end{cases}$$

Then

$$|A_1 + A_2 + A_3|^2 + |\alpha_1 A_1 + \alpha_2 A_2|^2 \leq \gamma_1 |A_1|^2 + \gamma_2 |A_2|^2 + \gamma_3 |A_3|^2.$$

Another extension of Bohr inequality is presented:

Corollary 5.3 If $A, B, C \in \mathbb{B}(H)$, and $\frac{1}{p} + \frac{1}{q} + \frac{1}{w} = 1, p, q, w \geq 0$, then

$$|A + B + C|^2 + \left| \frac{p}{\sqrt{p+q}}A - \frac{q}{\sqrt{p+q}}B \right|^2 \leq p|A|^2 + q|B|^2 + w|C|^2.$$

Theorem 5.4 Let $A_i \in \mathbb{B}(H)$, $\alpha_i, \beta_i \in \mathbb{R}$, $\gamma_i > 0$ with $i = 1, 2, 3$. If

$$\begin{cases} \gamma_1 \geq 1 + \alpha_1^2; \\ \gamma_2 \geq 1 + \alpha_2^2; \\ \gamma_3 \geq 1 + \alpha_3^2. \end{cases} \begin{cases} [\gamma_1 - (\alpha_1^2 + 1)][\gamma_2 - (\alpha_2^2 + 1)] \geq (\alpha_1\alpha_2 + 1)^2; \\ [\gamma_2 - (\alpha_2^2 + 1)][\gamma_3 - (\alpha_3^2 + 1)] \geq (\alpha_2\alpha_3 + 1)^2; \\ \alpha_1\alpha_3 + 1 = 0. \end{cases}$$

Then

$$|A_1 + A_2 + A_3|^2 + |\alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3|^2 \leq \gamma_1 |A_1|^2 + \gamma_2 |A_2|^2 + \gamma_3 |A_3|^2.$$

Corollary 5.5 If $A, B, C \in \mathbb{B}(H)$, and $\frac{1}{p} + \frac{1}{q} + \frac{1}{w} = 1, p, q, w \geq 0$, then

$$|A + B + C|^2 + \left| \frac{1}{\sqrt{w-1}}A + \frac{1}{\sqrt{w-1}}B - \sqrt{w-1}C \right|^2 \leq p|A|^2 + q|B|^2 + w|C|^2.$$

Related to [3], we have the following inequalities. As a matter of fact, the right-hand sides are regarded as the weighted arithmetic mean of $|A|^2$, $|B|^2$ and $|C|^2$ in [3, Lemma 1].

Corollary 5.6 If $A, B, C \in \mathbb{B}(H)$, and $t \in (0, 1)$, then we have

$$\begin{aligned} |A + B + C|^2 + |\sqrt{t}A + \sqrt{t}B - \frac{1}{\sqrt{t}}C|^2 &\leq \frac{2-t}{1-t} \frac{1+t}{t} |A|^2 + \frac{2-t}{1-t} |B|^2 + \frac{1+t}{t} |C|^2; \\ |A + B + C|^2 + |\sqrt{1-t}(A+B) - \frac{1}{\sqrt{1-t}}C|^2 &\leq \frac{1+t}{t} |A|^2 + \frac{2-t}{1-t} \frac{1+t}{t} |B|^2 + \frac{2-t}{1-t} |C|^2. \end{aligned}$$

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